Coherent electron Cooling Proof-of-Principle Experiment and Beam Use Request for Run 2022

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Vladimir N Litvinenko – project director

Jean Clifford Brutus – project manager

Vladimir N Litvinenko for the CeC group: Yichao Jing, Dmitry Kayran, Jun Ma, Irina Petrushina, Igor Pinayev, Kai Shih, Medani Sangroula, Gang Wang, Yuan Wu

Brookhaven National Laboratory and Stony Brook University

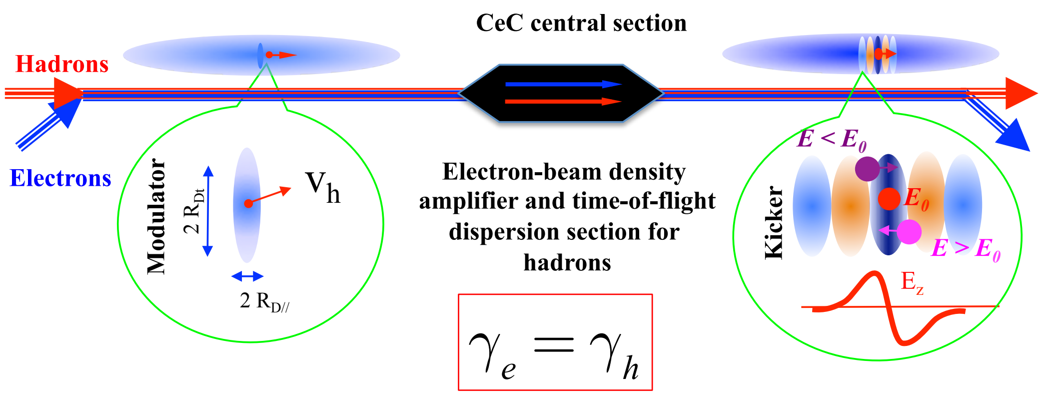
@BrookhavenLab

BNL NPP Program Advisory Committee Meeting, June 22, 2021

Coherent electron Cooling

All CeC systems are based on the identical principles:

- Hadrons create density modulation in co-propagating electron beam
- Density modulation is amplified using broad-band (microbunching) instability
- Time-of-flight dependence on the hadron's energy results in energy correction and in the longitudinal cooling. Transverse cooling is enforced by coupling to longitudinal degrees of freedom.



UM HE 91-28
August 7, 1991

COHERENT ELECTRON COOLING
1. Physics of the method in general

Ya. S. Derbenev
Randall Laboratory of Physics, University of Michigan
Ann Arbor, Michigan 48109-1120 USA

ABSTRACT

A microwave instability of an electron beam can be used for a multiple increase in the collective response for the perturbation caused by a heavy particle, i.e. for enhancement of a friction effect in electron cooling method. The low-scale instabilities of a few kind can be

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]
[1]Brookhaven National Laboratory, Upton, Long Island, New York, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

(Received 24 September 2008; published 16 March 2009)

PRL 111, 084802 (2013) PHYSICAL REVIEW LETTERS

Microbunched Electron Cooling for High-Energy Hadron Beams

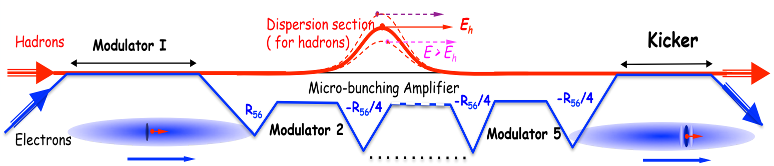
D. Ratner*
SLAC, Menlo Park, California 94025, USA

(Received 11 April 2013; published 20 August 2013)

What can be tested experimentally?

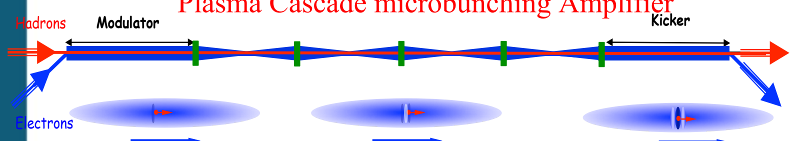
Litvinenko, Derbenev, PRL 2008

Ratner, PRL 2013

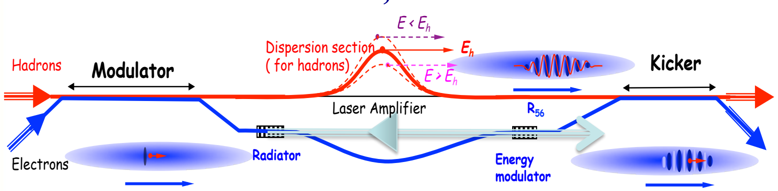


Litvinenko, Wang, Kayran, Jing, Ma, 2017

Plasma Cascade microbunching Amplifier



Litvinenko, Cool 2013



RHIC Run 18

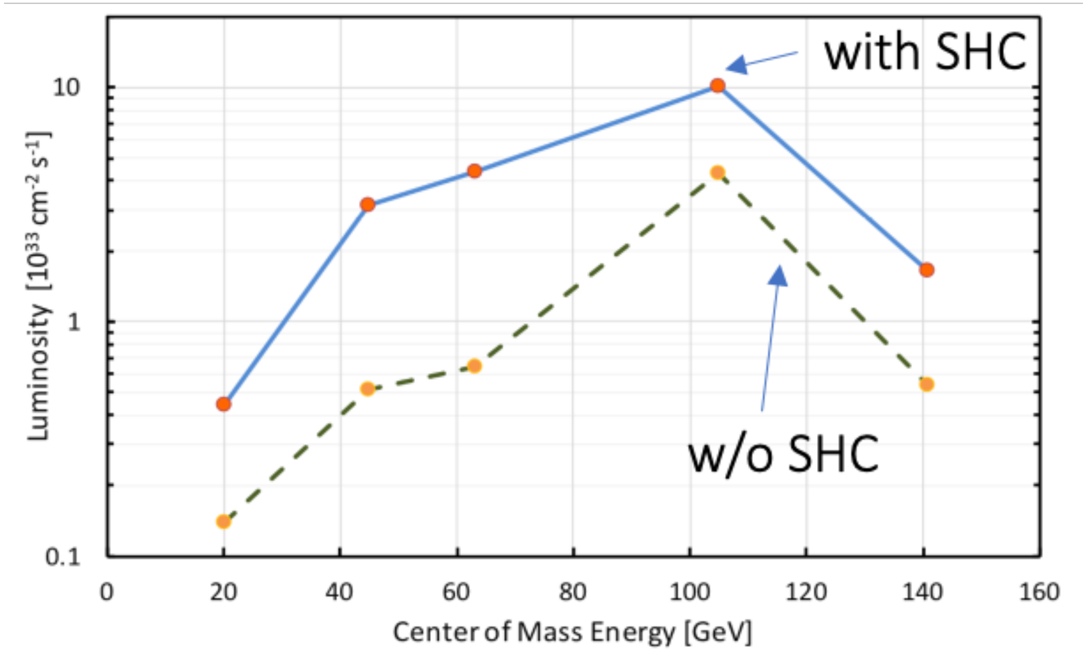
Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

RHIC Runs 20-22

Cooling test would require significant modification of the RHIC lattice & superconducting magnets quadrupling the cost

Derbenev is suggesting to explore CSR as an CeC amplifier

Why strong hadron cooling is needed?



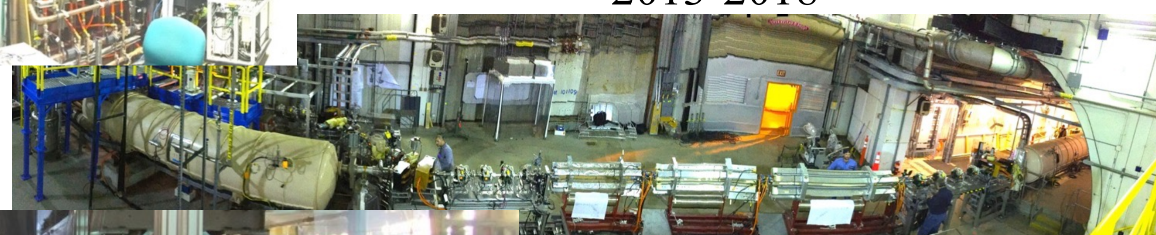
- National Academy of Sciences Assessment of U.S.-Based Electron-Ion Collider Science: *The accelerator challenges are two fold: a high degree of polarization for both beams, and high luminosity.*

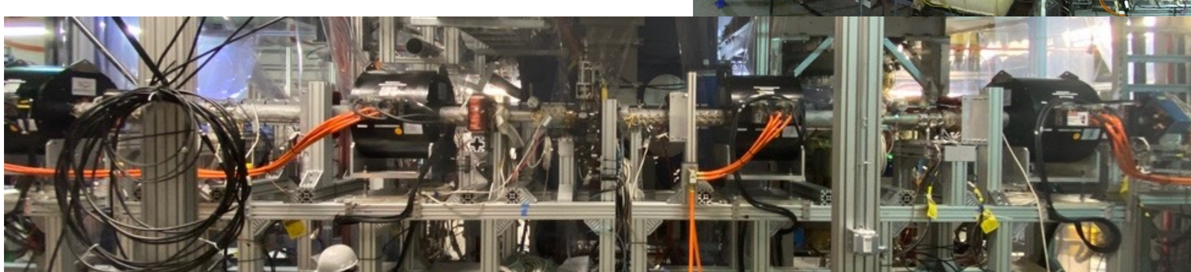
Why we need the CeC experiment?

Quote from the pCDR review committee report:

"The major risk factors are strong hadron cooling of the hadron beams to achieve high luminosity, and the preservation of electron polarization in the electron storage ring. The Strong Hadron cooling [**Coherent Electron Cooling (CeC)**] is needed to reach $10^{34}/(cm^2 s)$ luminosity. ***Although the CeC has been demonstrated in simulations, the approved "proof of principle experiment" should have a highest priority for RHIC***."

2013-2018

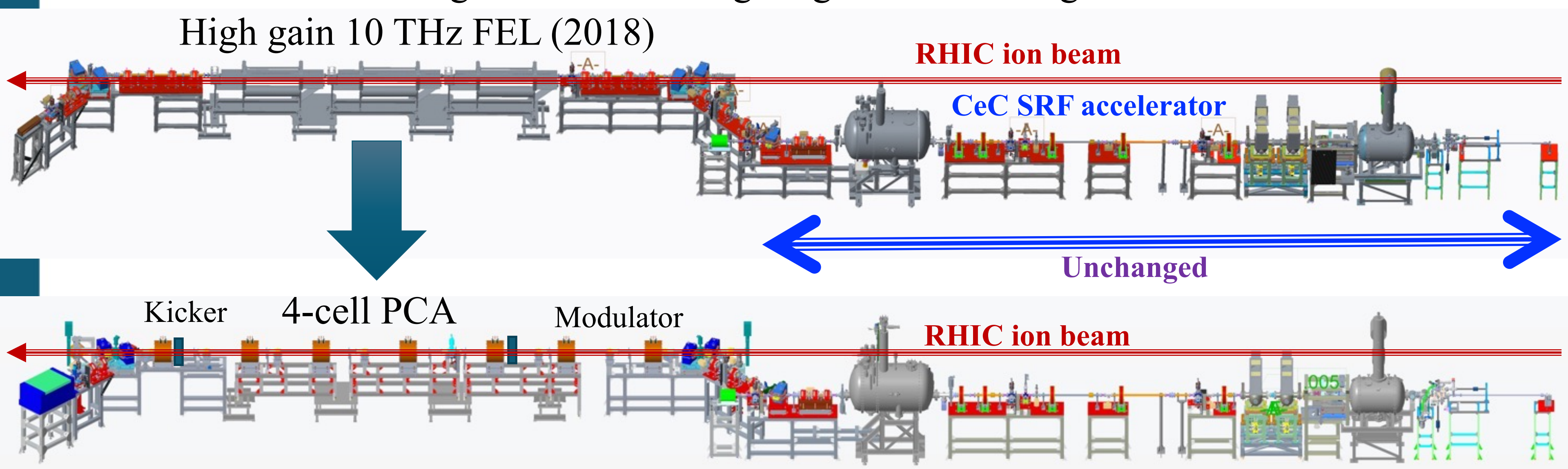




2019-present

CeC experiment at RHIC

- 2014-2017: built cryogenic system, SRF accelerator and FEL for CeC experiment
- 2018: started experiment with the FEL-based CeC. It was not completed: **28 mm** aperture of the helical wigglers was insufficient for RHIC with 3.85 GeV/u Au ion beams
- We discovered microbunching Plasma Cascade Instability - new type of instability in linear accelerators. Developed design of Plasma Cascade Amplifier (PCA) for CeC
- In 2019-2020 a PCA-based CeC with seven solenoids and vacuum pipe with **75 mm** aperture was built and commissioned. During Run 20, we demonstrated high gain Plasma Cascade Amplifier (PCA) and observed presence of ion imprint in the electron beam
- New time-resolved diagnostics beamline was built last year and commissioned during this run. Now we focusing on demonstrating longitudinal cooling.



The CeC Plasma Cascade Amplifier has a bandwidth of 15 THz >2,000x of the RHIC stochastic cooler

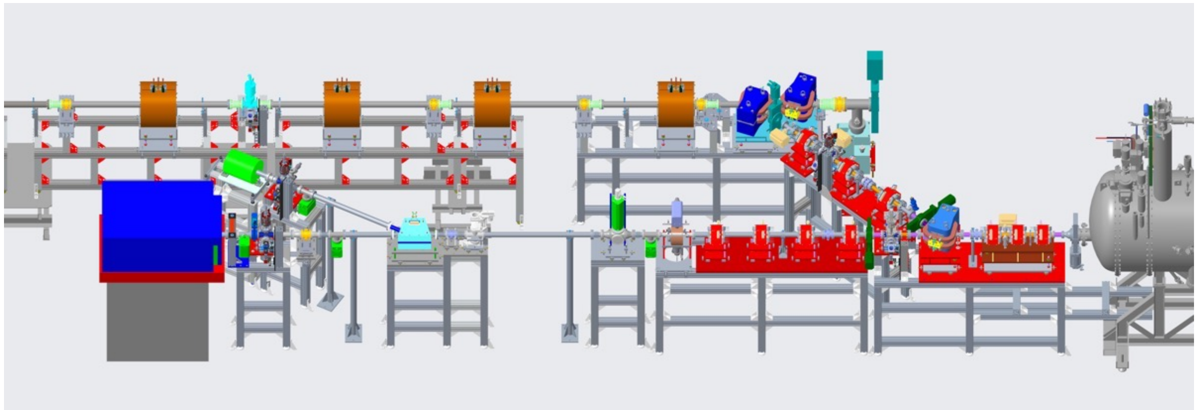
Run 21: Major disruption of the project

We lost 7 weeks of operation during this run because of the damage to our SRF gun

- The UHV cathode transport and positioning system was severely damaged – and it was not the result of operations performed by the CeC engineers, technicians and scientist. C-AD completed the investigation and filed report to DOE.
- It resulted in burn-off of cathode mount and severe contamination of the SRF gun and the cathode transfer system
- It took enormous efforts to restore the SRF gun operation
  - The cathode transfer system had to be fully disassembled and rebuilt
  - The SRF gun went through an elaborate, labor-intensive and previously untested procedures to it clean-up and to burn-off debris
  - Luckily, we were able to restore – and even improve – the SRF gun cavity performance
  - Poor quality of the photocathodes remains a problem, which we hope to overcome for next run
- As a result of this damage, we lost 7 week of operations, which we are still trying to catch up with.

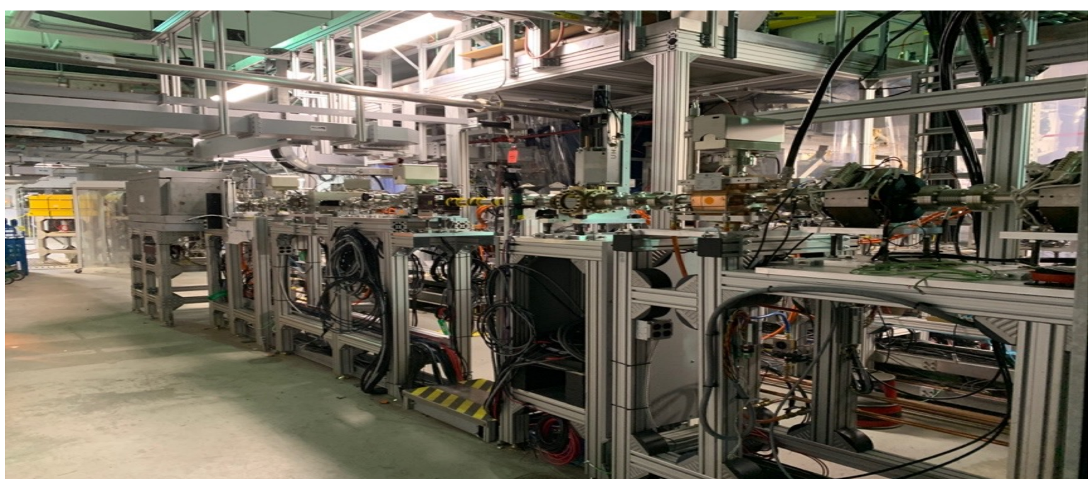
Brookhaven National Laboratory

Time-resolve diagnostics beam-line



Fully Commissioned

- Run 21 main addition is the time-resolved diagnostics beam-line
  - To evaluate local beam quality of electron beam with time resolution of 1 psec
  - Played critical role for achieving Key Performance Parameter for this run



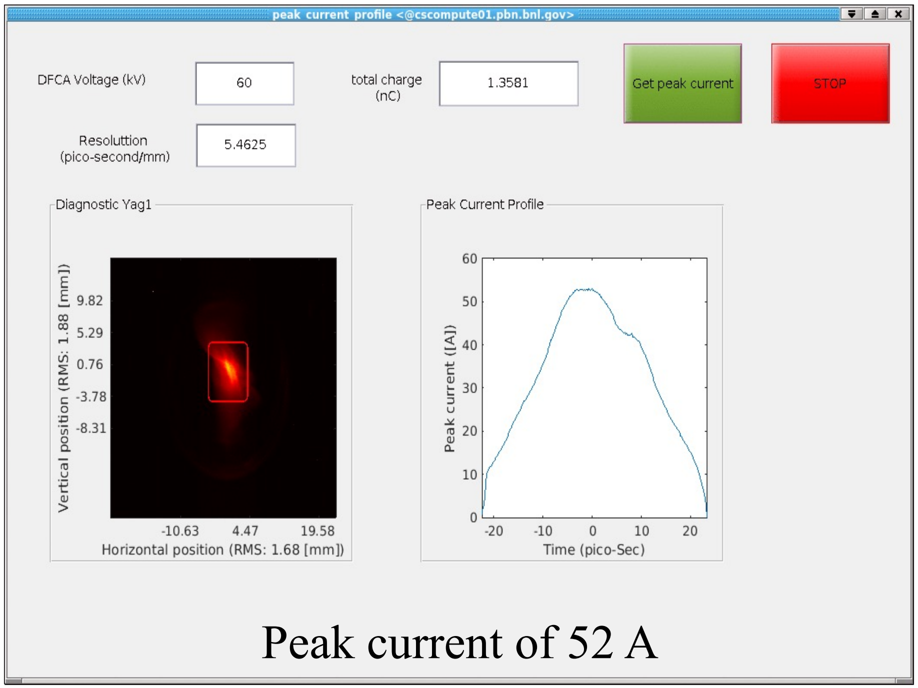
Key Performance Parameters (KPP)

Electron beam KPP

Parameter	Planned	Demonstrated	
Lorentz factor	28.5	up to 29	✓
Repetition frequency, kHz	78.2	78.2	✓
Electron beam full energy, MeV	14.56	up to 14.8	✓
Total charge per bunch, nC	1.5	nominal 1.5, up to 20	✓
Average beam current, μA	117	120	✓
Ratio of the noise power in the electron beam to the Poison noise limit	<100	<10 (lattice of Run20)*	***
RMS momentum spread $\sigma_p = \sigma_p/p$, rms	$\leq 1.5\times10^{-3}$	$<5\times10^{-4}$, slice 2×10^{-4}	✓
Normalized rms slice emittance, μm rad	≤ 5	2.5	✓

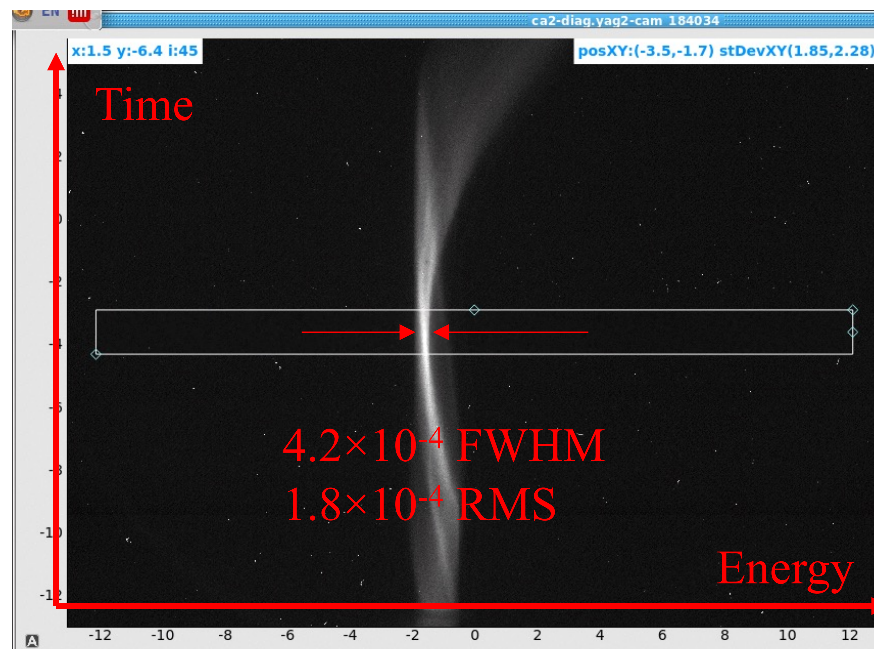
*** *In order to save preparation time and to catch-up with the plans after significant time lost caused by the damage to the SRF gun, we did not repeat lengthy measurements of the beam noise, which were performed during Run 19 and Run 20. Instead, we are repeating the setting used to achieve necessary low noise level in the beam.* Noise measurement will be performed parasitically during our attempt to demonstrate CeC cooling.

Beam peak current and energy spread



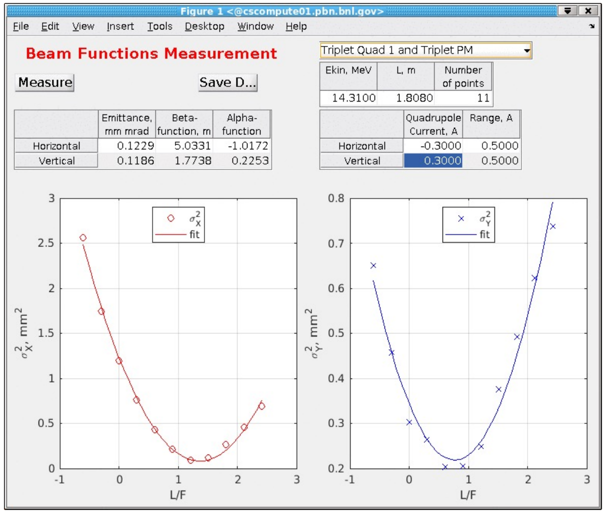
Peak current of 52 A

Direct pass

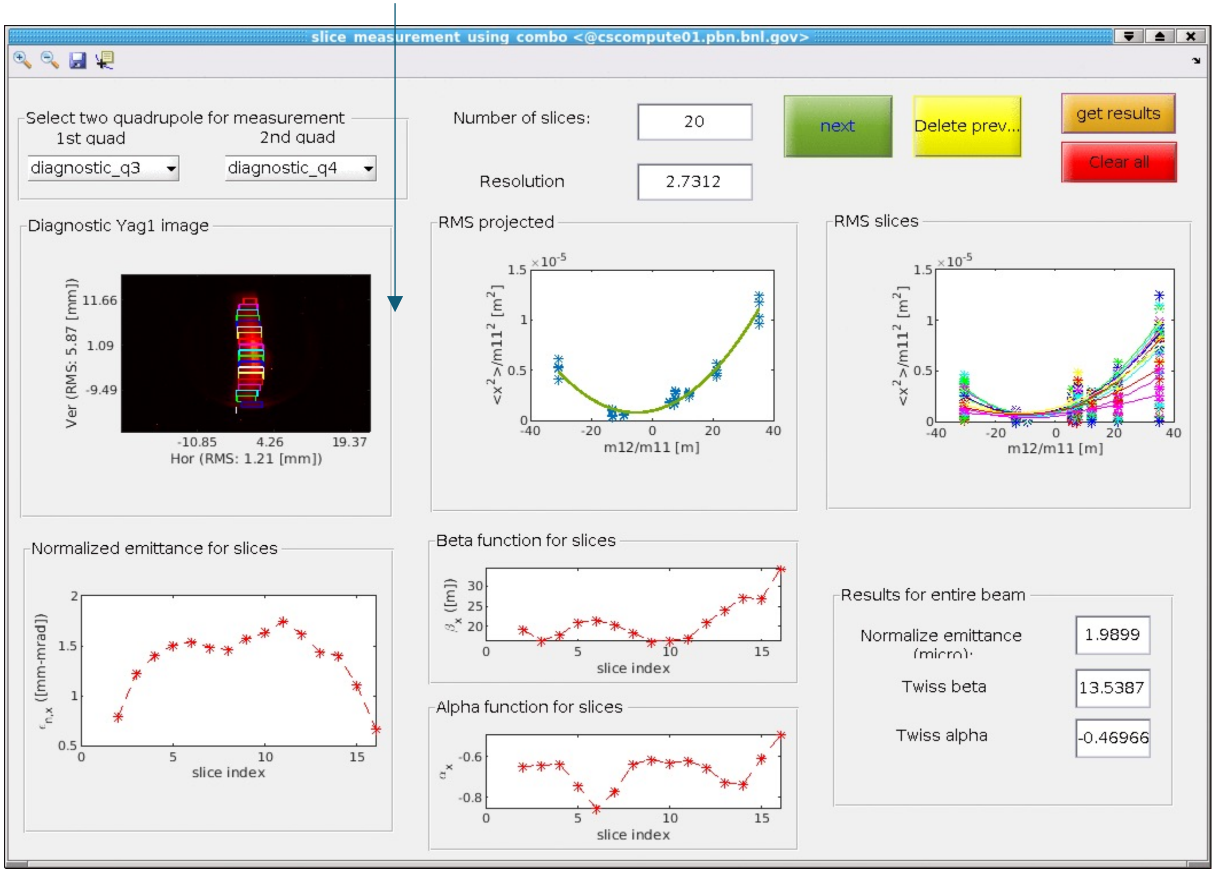


30-degree energy spectrometer

Beam emittance



Quadrupole scan in the triplet section:
Measured normalized emittances are 3.5 μm for horizontal and 3.4 μm vertical



Time resolved horizontal slice beam emittance with normalized emittances of the beam core bellow 2 μm

Beam-Based Alignment for CeC solenoids

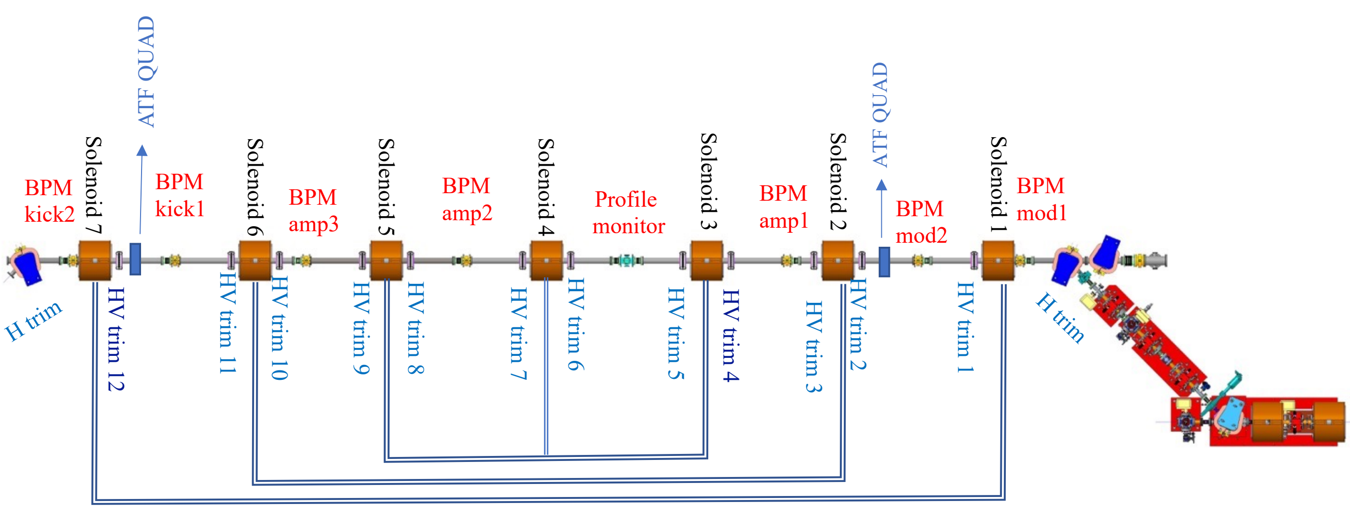
Accurate alignment of the electron beam trajectory is critically important for operation of the PCA-based CeC. This year we completed this process

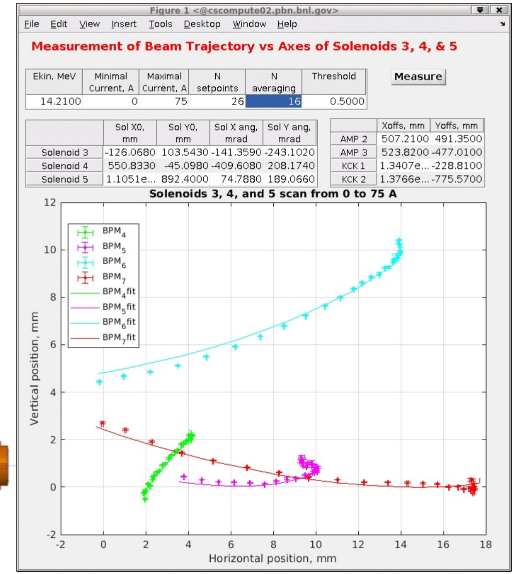
First, we aligned ion beam with centers of two quadrupoles in the CeC section

Second, we accurately measured both location and the angle of the solenoid's axes using ion beam and RHIC BPM – this is a novel method that we developed. Solenoids then were aligned with best accuracy the survey group can provide

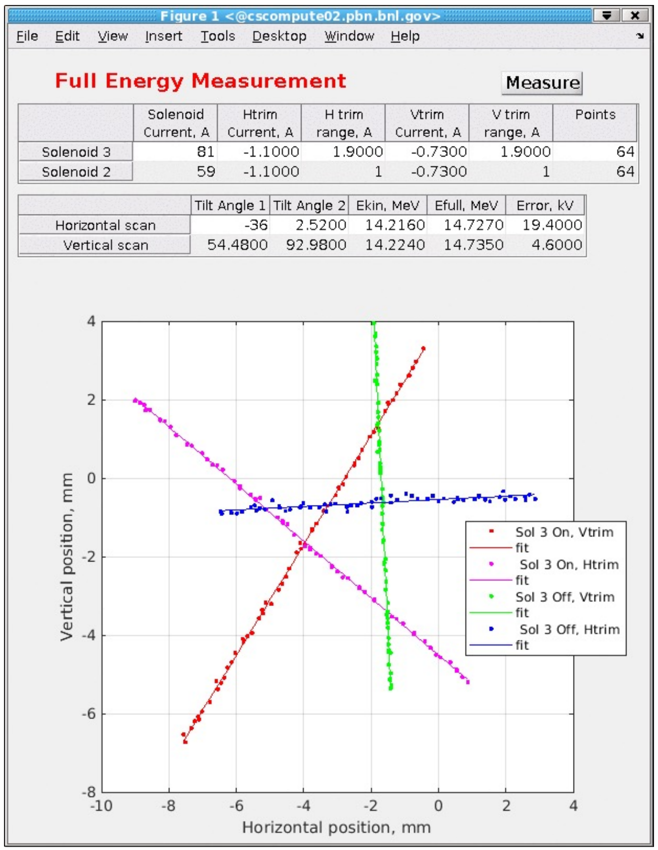
Third, during the last month after a number of set-backs, we aligned electron beam with axes of solenoids

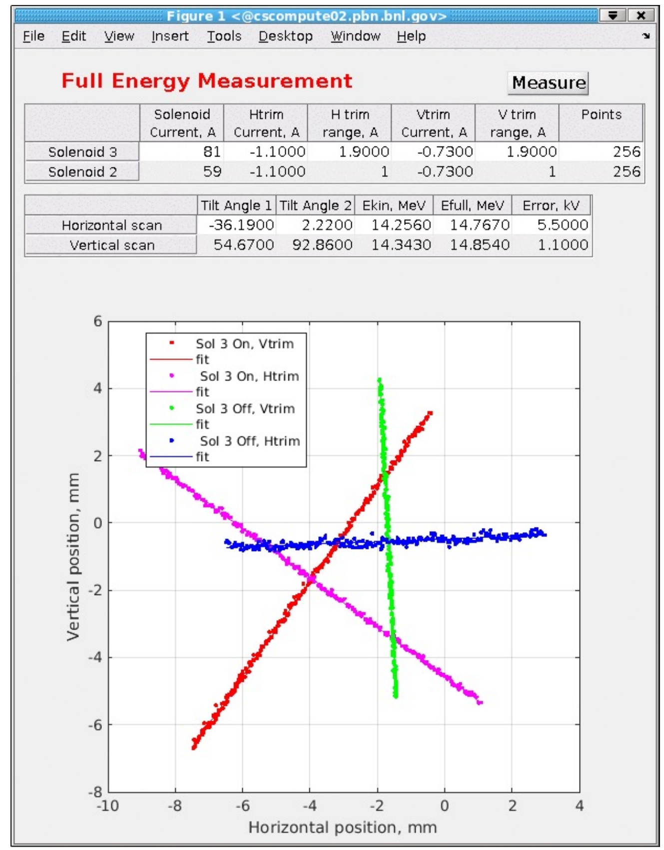
This is a new technique we developed to guarantee overlapping of electron and ion beams





Beam energy measurement in the CeC

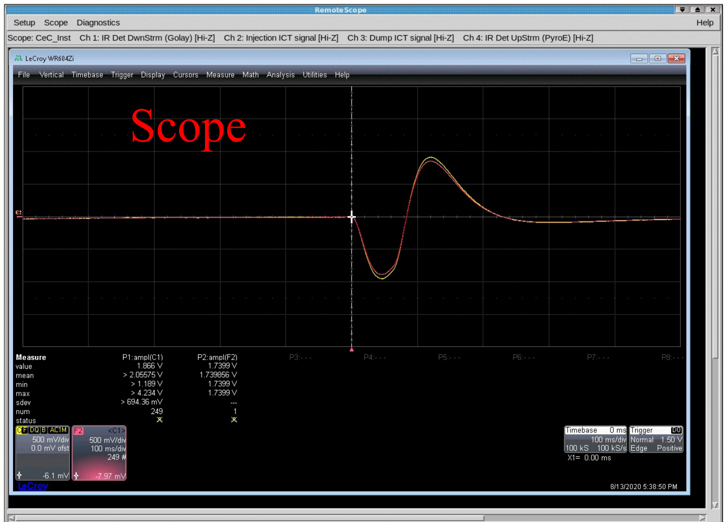


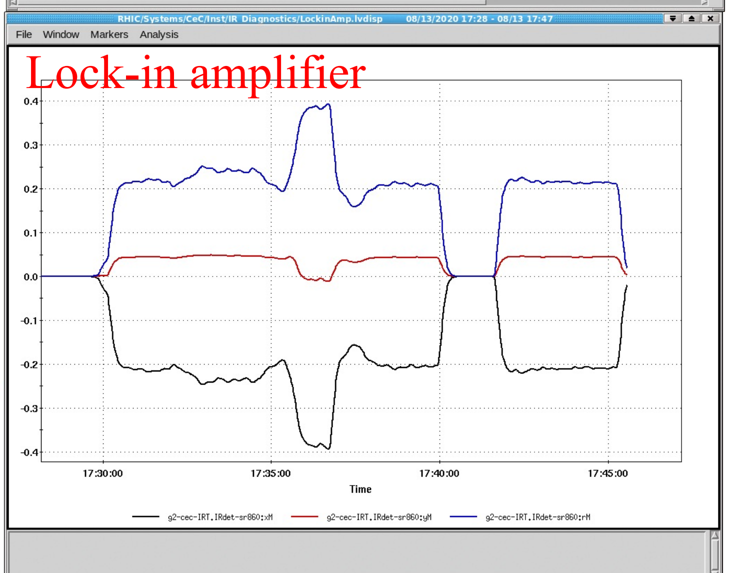


Novel method of absolute beam energy measurement – based on Ampere law and knowing value of current and number of turns in solenoid:
Current accuracy ~ 0.2%. Main source of errors is in the orbit jitter.

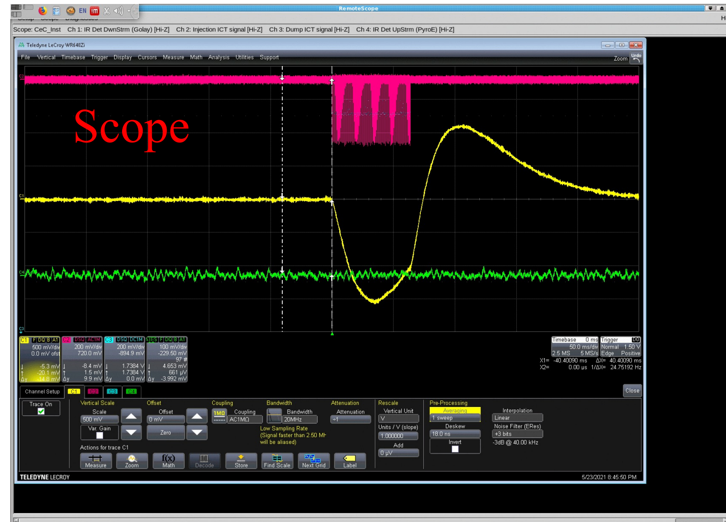
Restoring high-gain PCA

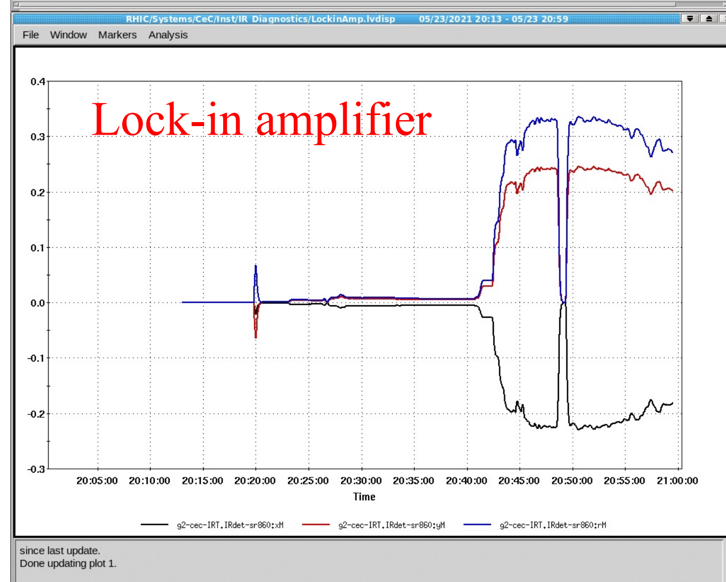
Run 20





Run 21, May 23, 2021





Reportable Milestones

Milestone ID	Reportable milestone	Date
1	Experiment start	FY20Q1
2	Necessary Beam Parameters (KPP) established for Run 20	FY21Q4
3	Investigation of plasma cascade amplifier complete	FY21Q4
4	Investigation of the ion imprint in the electron beam complete	FY22Q1
5	Receive Approval for CeC TRDBL commissioning	FY22Q1
6	Necessary Beam Parameters (KPP) established for Run 21	FY22Q3
7	Investigation of the CeC longitudinal cooling complete	FY22Q4
8	Necessary Beam Parameters (KPP) established for Run 22	FY23Q3
9	Investigation of the 3D CeC Cooling complete	FY23Q4
10	Final report to DOE NP	FY23Q4
11	Experiment Complete	FY23Q4

CeC goals during RHIC Run 21

- Build and commission new time-resolve diagnostics beam line – Done
- Demonstrate key beam parameters (KPP) for RUN 21 – Done
- Restore operation of Plasma-Cascade Amplifier – Done
- Demonstrate longitudinal cooling of 26.5 GeV/u ion beam is in progress.

  While electron beam parameters are satisfactory, stability and repeatability remain main problem for the experiment. They are result of the large – up to 100 psec - time jitter of the drive laser and drifting phases and voltages in three RF systems. Measuring and correcting parameters of RF system is time consuming and slows down the studies. There is a chance that cooling test would extend into Run 22.

- Notes
  - Because of COVID-19 pandemic, we added 12-month operation contingency to the CeC project: longitudinal cooling milestone is moved to FY 22, we are following so called "early" schedule
  - We requested 2 weeks of dedicated time for Run 21, we used ~ 65% up to date.
  - There was a major damage to our SRF gun, which we managed to overcome, but we lost about 7 weeks of operation. Because of this serious set-back we may need additional dedicated time this run

Brookhaven National Laboratory

Plan to mitigate current problems

- We procured seed laser which has 4 times smaller jitter from French company – it arrived one three weeks ago, but we are not allowed to open it without so-called “assession number”(which means – equipment tag number!) from FDA. Unfortunately, FDA bureaucracy works slow and in best case scenario they promise for issue such number in 3-4 weeks. It will be too late for this run, but will be likely in time for start of the next run in November 2021.
- We work with the RF group engineers to identify underlying reasons of these drifts. The RF group applied all modern methods – called loop-back- of compensating for the temperature dependence of the time delays and losses in cables, but there is something else which causes these drifts. We are in the process of collecting information and we are confident that we will identify and eliminates the cause(s).

Coherent electron Cooling Beam Use Request for Run-22*

- **Demonstration of 3D ion beam cooling using the PCA-based CeC**
- Re-establish the Run 21 mode of operation — 6 shifts
- Re-establish longitudinal cooling of 26.5 GeV/u Au ion beam — 12 shifts
- Develop lattice for coupling of longitudinal to transverse cooling — 6 shifts
- Demonstrate 3D cooling of 26.5 GeV/u Au ion beam — 24 shifts
- **Total — 48 shifts (16 days)**
- **Contingency — 15 shifts (5 days)**

** This is the plan for "early completion of the CeC project": it assumes that longitudinal CeC cooling is demonstrated during Run 21. Contingency plan will have the same BUR as we submitted for Run 21*

Beam Use Request

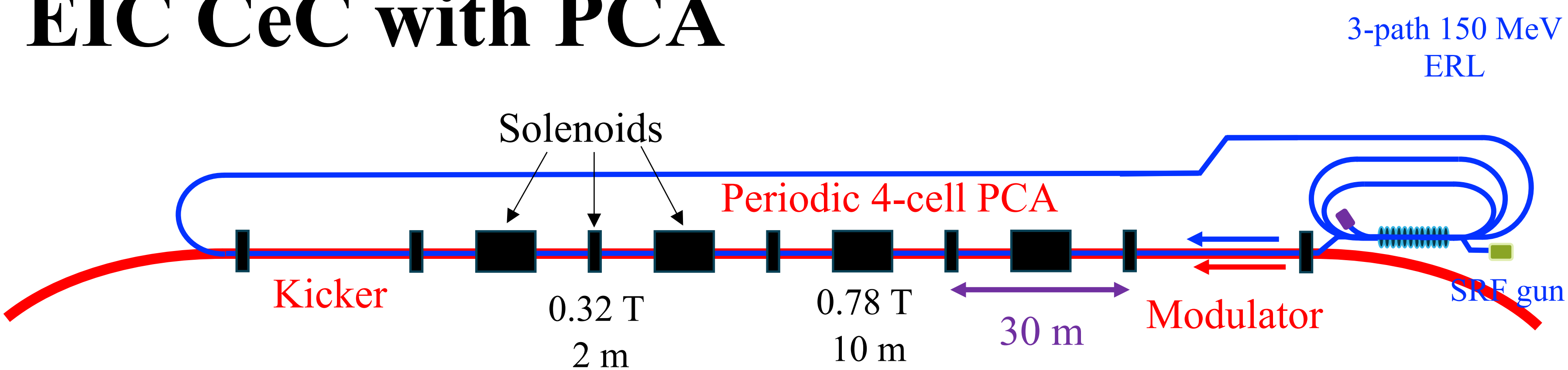
- We propose to complete Coherent electron Cooling demonstration experiment using the unique and only facility testing the cooling technique capable of cooling EIC beams
- We demonstrated presence of the ion imprint and high gain of plasma-cascade amplifier in our Run 20
- We request 16 days of the dedicated time for this experiment in Run 22
- Contingency plan for this experiment may require additional run in FY 23

Summary

- We are making steady – even though slower that we would like – progress towards testing CeC with an ion beam. Plasma-cascade amplifier operation is restored.
- We still aiming to demonstrate cooling during this run but there is a possibility that cooling demonstration would extend into Run 22.
- Currently the CeC operations are suspended by reason of “possible ASE violation”. Note that it was demonstrated that there are no safety issues from operating CeC.
- CeC team is very busy with the experiment, but when we have time, we use it to work on a cost-effective design of CeC for EIC

Brookhaven National Laboratory

EIC CeC with PCA



Name	Current experiment	CeC cooler for EIC
PCA Lattice	Periodic, 4 cells, regular	Periodic, 4 cells, optimized
γ	28.5	293
Hadrons	Au ions	Protons
E_h, GeV	26.5	275
E_e, MeV	14.56	150
l, m	2x1	2x15
a_0, mm	0.2	0.15
Q, nC	1.5	1.5
I_0, A	75	150
ε_{norm}, m	$5\ 10^{-6}$	$5\ 10^{-6}$
Frequency, THz	25	500
PCA gain	100	400
Lattice	regular	1:2
3D emittance Cooling time, min	15-20	<5

The CeC team – never can get all your pictures …

Recent Refereed Publications

Simulations of Coherent Electron Cooling with Two Types of Amplifiers, Jun Ma, Gang Wang, Vladimir Litvinenko accepted for Special Issue "Charged Particle Optics and Computational Accelerator Physics (CPO-10/ICAP'18)" , **International Journal of Modern Physics A (IJMPA),** Vol. 34 (2019) 1942029 (17 pages), Accepted 19 May 2019, Published 11 December 2019

Evolution of ion bunch profile in the presence of longitudinal coherent electron cooling, Gang Wang, **Physical Review Accelerators and Beams** (2019).

High brightness CW electron beams from Superconducting RF photoemission gun, I. Petrushina, V.N. Litvinenko, Y. Jing, J. Ma, I. Pinayev, K. Shih, G. Wang, Y.H. Wu, J.C. Brutus, S. Belomestnykh, Z. Altinbas, A. Di Lieto, P. Inacker, J. Jamilkowski, G. Mahler, M. Mapes, T. Miller, G. Narayan, M. Paniccia, T. Roser, F. Severino, J. Skaritka, L. Smart, K. Smith, V. Soria, Y. Than, J. Tuozzolo, E. Wang, B. Xiao, T. Xin, S. Belomestnykh, I. Ben-Zvi, C. Boulware, T. Grimm, K. Mihara, D. Kayran, and T. Rao, **Phys. Rev. Lett**. 124, 244801 (2020)

Using solenoid as multipurpose tool for measuring beam parameters, Igor Pinayev, Yichao Jing, Dmitry Kayran, Vladimir N. Litvinenko, Jun Ma, Kentaro Mihara, Irina Petrushina, Kai Shih, Gang Wang, Yuan Hui Wu, **Review of Scientific Instruments** 92, 013301 (2021),

Plasma-Cascade Instability, Vladimir N. Litvinenko, Yichao Jing, Dmitry Kayran, Patrick Inacker, Jun Ma, Toby Miller, Irina Petrushina, Igor Pinayev, Kai Shih, Gang Wang, Yuan H. Wu, **Physical Review Accelerators and Beams** 24, 014402 (2021)

Long lifetime of bialkali photocathodes operating in high gradient Superconducting Radio Frequency gun, E. Wang, V.N. Litvinenko, I. Pinayev, M. Gaowei, J. Skaritka, S. Belomestnykh, I. Ben-Zvi, J.C. Brutus, Y. Jing, J. Biswas, J. Ma, G. Narayan, I. Petrushina, O.Rahman, T. Xin, T. Rao, F. Severino, K. Shih, K. Smith, G. Wang, Y. Wu, *accepted to* ***Scientific Reports****, February 8, 2021*

Theory of Plasma-Cascade Instability, Vladimir N. Litvinenko, Gang Wang, Yichao Jing, Jun Ma, Irina Petrushina, Kai Shih, Yuan H. Wu, submitted to **Physical Review Accelerators and Beams**, May 2021